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INTEGRATED MATHEMATICAL MODELLING AS A BASIS FOR DECISION MAKING IN WATER MANAGEMENT

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Abstract. Water resources development and management is a complex problem. It includes the design and operation of single system components, often as part of larger interrelated systems and usually on the basis of river basins. While several decades ago the dominant objective was the maximization of economic benefit, other objectives have evolved as part of the sustainable development envisaged. Today, planning and operation of larger water resources systems is practically impossible without adequate computer tools, normally being one or several models, increasingly combined with data bank management systems and multi criteria assessment procedures in decision support systems. The use of models in civil engineering already has a long history when structural engineering is considered. These design support models, however, must rather be seen as expert systems made to support the engineer with his daily work. They often have no direct link to stakeholders and the decision makers community. The scale of investigation is often much larger in water resources engineering than in structural engineering which is related to different stakeholders and decision making procedures. Still, several similarities are obvious which can be summarized as the search for a compromise solution on a complex, i.e. multiobjective and interdisciplinary decision problem. While in structural engineering e.g. aestetics, stability and energy consumption might be important evaluation criteria in addition to construction and maintenance cost other or additional criteria have to be considered in water resources planning such as political, environmental and social criteria. In this respect civil engineers tend to overemphasize technical criteria. For the future the existing expert systems should be embedded into an improved decision support shell, keeping in mind that decision makers are hardly interested in numerical modelling results. The paper will introduce into the problem and demonstrate the state of the art by means of an example.

1 INTRODUCTION

Integrated water management has evolved from sectorial planning due to changing objectives. The paradigm of sustainable water management now requires integrative and interdisciplinary approaches combining multiple objectives being technological, economic, ecologic and social in nature at the same time. Decision making on complex and interdisciplinary , so-called ill based problems needs adequate support. Figure 1 shows the integrated set of values being agreed upon in the German engineering sector.

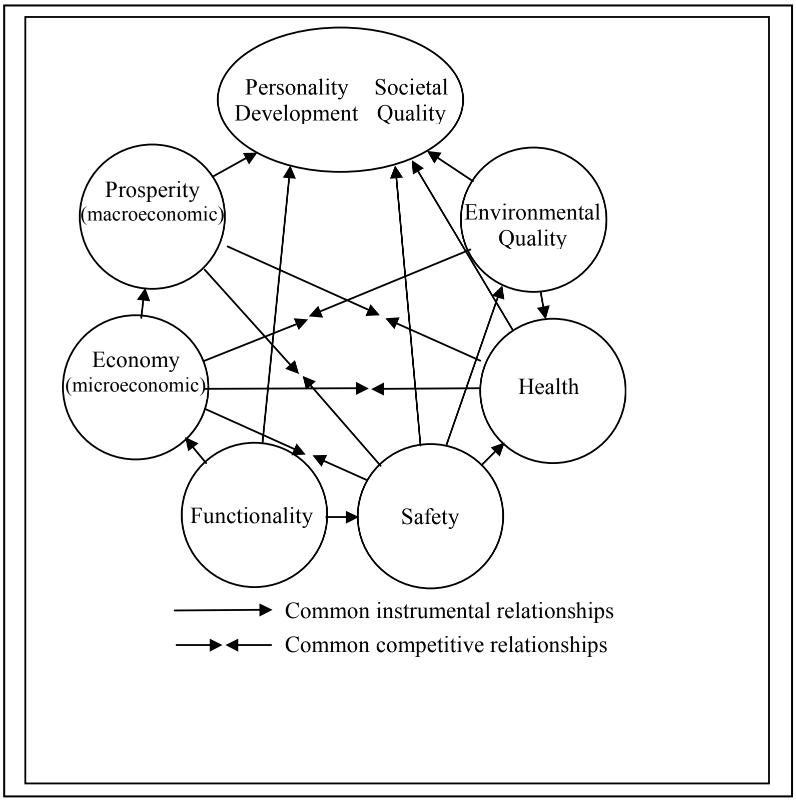


Figure 1: Values in technical action according to VDI [1]

A recent European movement towards an overall good ecological status of our water bodies, both surface and sub-surface has initiated an extended and longterm movement towards integrated modelling of water resources systems. Soon it became evident that the answer to the question cannot be the development of a completely new integrated model. Instead, the coupling and integration of existing compartment models is underway, which are related to different disciplines. A representation is given in Figure 2. In water management a wide variety of models is used starting from a simple set of empirical equations up to three dimensional physically based numerical representations of the water management systems to be analysed and decided upon. Increasingly, these are combined with methods for the optimum choice of alternatives and model parameter estimation.

Disciplines involved stem from engineering, natural and social/human sciences. It is obvious that communication and cooperation between these sciences is difficult, which is e.g. due to the lack of a common language required for broader understanding, but is also

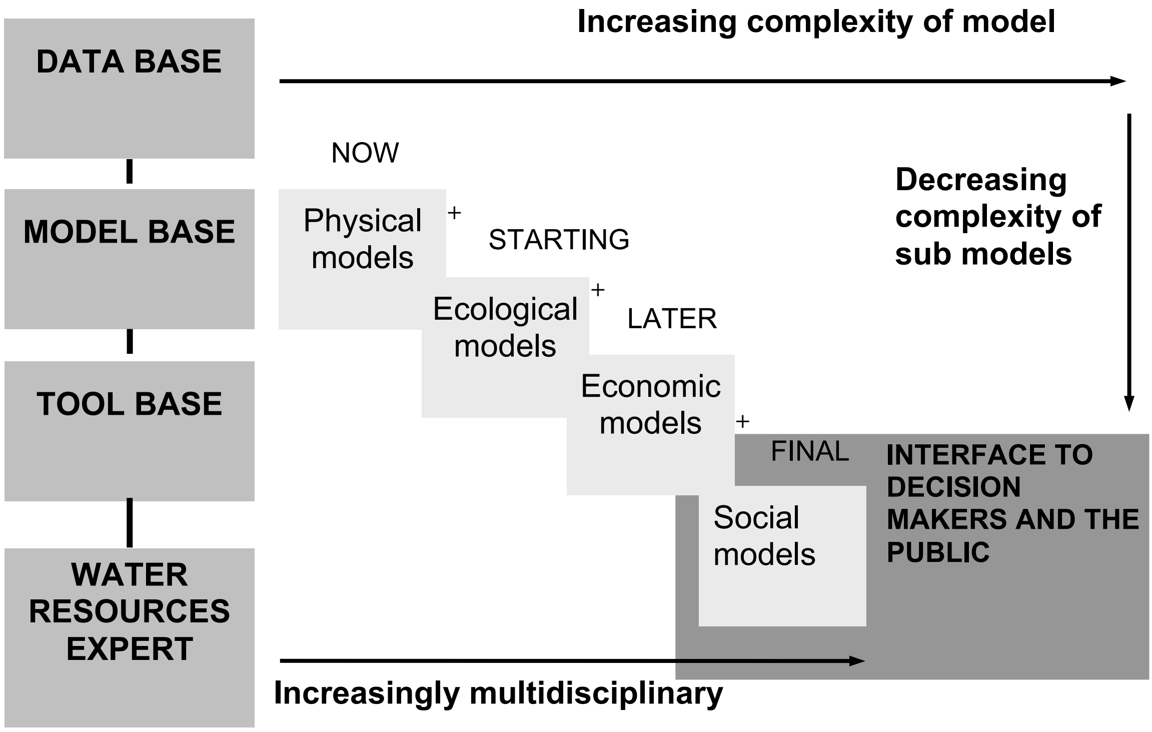


Figure 2: The model base of a DSS [2]

caused by very widespread mutual ignorance. It is also evident that those disciplines which are not interested in applied sciences can hardly play a remarkable role in integrated water management.

From the modellers point of view it seems to be necessary to understand what is needed for the decision maker to come to a good decision. Mostoften, this is not the modelling result itself, but the significance of a result with respect to a multiple set of conflicting objectives translated into tangible or intangible criteria. To achieve improved acceptance of modelling results better transparent interfaces are needed to translate their basic significance to stakeholders involved in the process.

2 INTEGRATED MODELLING

Integrated modelling in water resources can have different purposes, domains and structures. Classification of models to be integrated into systems is in progress, but no general agreement has been reached yet. Concerning a classification one might differentiate between several purposes, domains and model structures.

2.1 Model purpose

Design models support the dimensioning and layout of hydraulic infrastructure similar to structural engineering. In contrast to structural engineering, these single hydraulic structures, however, are often embedded in complex water resources systems. Thus, system interactions between system elements have to included in the design.

Operation models assist in identifying optimum mean or long term operation rules. Once a water resources system has been developed, it has to be operated in an optimum way for a selected set of partly contradicting objectives. For this purpose the system has to be simulated and optimized using adequate optimisation procedures. Due to the form of the objective functions and the structure of the systems under consideration dominantly search techniques are used except in very simple cases when mathematically proved algorithms might be applied.

Forecasting and realtime control models serve the purpose to predict extreme hydrometeorological, geotechnical (and other) events such as floods, droughts or dambreaks. In contrast to operation models realtime control models support decisions on adequate actual reactions to extreme situations.

2.2 Model domains

In the past models have been developed by different sections of water management often represented by different scientific disciplines. Without claiming to be complete Table 1 gives an overview of different modelling approaches frequently applied at present. Only water quantity is considered in the table, but it must be stressed that increasingly conservative and non conservative water constituents such as pollutants and nutrients are modelled simultaneously.

Domain modelled	Size	Time step	Solution	Diff. Eq.
Hydrologic River Basin	10 – 10.000 km^2	15 min – 1 day	Analytical	MBE
Urban catchment	1- 100 ha	5 – 30 min	Analytical	MBE
Urban sewer models	100 – 10.000 elements	1 sec – 5 min	Numerical	MEBE
River channel	100m – 1000 km	1 – 60 min	Numerical	MEBE
Reservoir	1- 300 hm^3	1 h – 1 day	Numerical	MBE
Groundwater body	1-100 km^2	1 – 14 days	Numerical	MEBE

Table 1: Frequently applied models in water management for different domains (MBE Mass balance equations, MEBE Coupled mass and energy balance equations)

2.3 Model structure

The domains explained above are often directly related to specific temporal and spatial scales as well as specific mathematical formulations including their type of solutions, e.g. analytical or numerical. In water resources engineering several model structures are differentiated. They range from empirical via conceptual to physically based models. In principal, all model structures might be applicable on all temporal and spatial scales. However, in general empirical models are applied on larger spatio-temporal scales than conceptual models. The smallest scales are usually required and applied for physically based mathematical models with numerical solutions such as two and three dimensional numerical hydrodynamic models for shallow water waves in open and closed, eventually surcharged flow systems.

2.4 Submodel integration

The integration of submodels with different purpose, for different domains and with different structure into one modelling system cannot be expected to be simple. Figure 3 gives an example of a basic water resources system. Even for such a system a hydrological rural model, a reservoir model, an urban drainage model, a groundwater model, a water distribution model and a hydrodynamic river model must be applied in an combined manner to account for integrated water management.

The application of linked models in water resources engineering is not new. First attempts were made several decades ago by US American water boards, e.g. the Tennessee Valley Authority TVA [3]. Other modelling packages followed, e.g. the Hydrologic Simulation Package Fortran HSPF supported by the United States Geological Survey USGS [4] , the Stormwater Management Model SWMM maintained by the United States Environmental Agency EPA [5]. Also commercial software producers put much effort into coupled models such as the Danish Hydraulic Institute DHI [6] to give a few examples.

The integration of submodels can be acchieved by very different approaches. In the simplest case data transfer between modules happens through individually tailored ASCII interfaces, submodels are run sequentially in time. In many cases, however, feedback control processes occur between submodels, which requires communication in a single time step in both directions. This has been frequently achieved through re-engineering of submodels in a way to put the time loop outside of the process simulation. Different submodels have been integrated by putting them into a common shell, again through tailored simulation control algorithms.

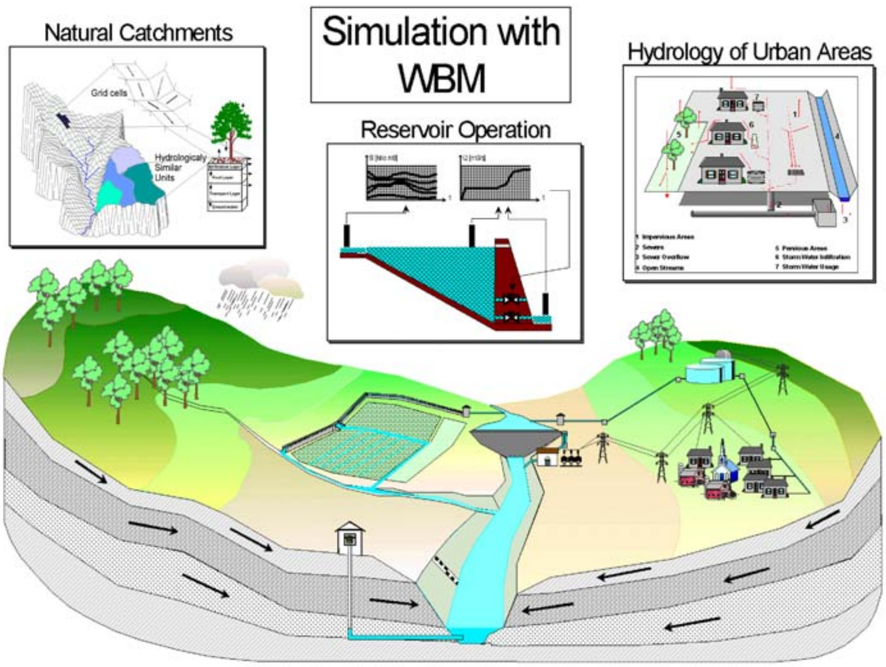


Figure 3 Basic water resources system simulated with an integrated model

Only recently a generalised interface was invisaged in a European Research Project HarmonIT. In this project, public and private research and development institutions developed the standard interface OPENMI [7] which has been published as open sources, which proved that such a standard interface is possible. Whether the interface will be accepted for practical use will become evident in the near future after several test applications will be accomplished.

Increasingly, the design and operation of water resources systems is supported by optimisation search algorithms, e.g gradient search or genetic/evolutionary algorithms. These algorithms are based on simulation, being combined with the integrated model in one shell, leading to even higher overall system complexity and exponential computational requirements. For ease of application and increased efficiency such shells have graphical user interfaces (GUI).

2.5 Numerical effort

Integrated water resources simulation/optimisation systems, especially when applied in long term simulation mode, require powerful computational resources definitely exceeding even high end single personal computers. For accelerated computation two approaches are available. On the one hand parallel computing becomes feasible even in engineering offices due to the production of multiple processor PC’s. These units are highly effective for speeding up numerical solutions in single submodels after reengineering based on parallel compilation. They are less helpful, however, to support the effective interaction of multiple computational modules.

For this purpose the use of distributed systems is probably the better approach. In the near future a distributed computer system including the required number of multiple processor machines will be most likely the best solution for the existing computational problems.

3 DECISION SUPPORT SYSTEMS

The development of decision support systems (DSS) is en vogue in water resources systems, although a clear definition of the term is still missing. Obvious, however, is a misinterpretation of the term mainly by engineers. Frequently engineers are using the term DSS when they mean modelling expert systems. In general a decision support system DSS includes modelling, but not necessarily those models applied by civil engineers.

A DSS provides the platform for interactive decision making. In water resources engineering it is essential that all important stakeholders are included in the decision process. To come to a generally accepted decision, stakeholders should be included as early as possible. A future oriented planning procedure comprises the following steps:

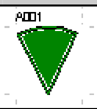
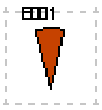
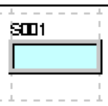
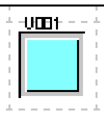
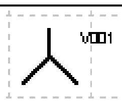
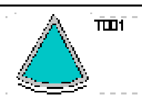
- Define planning objective(s)
- Chooses evaluation criteria (economic, ecologic, social, technical)
- Assume external development scenarios (population growth and migration, economic growth, climate change)
- Choose a set of feasible solutions (alternatives) including the zero option
- Analyse the set of feasible solutions mostly by means of computer modelling including optimisation
- Compare the performance of solutions against the agreed set of criteria
- Decide on the best solution or go back to earlier steps.

Often this process is an iterative process. No optimum solution might be identified in the first round, requiring feedbacks to earlier planning/decision steps. It is evident that in the decision making process modelling plays a very limited role. The majority of stakeholders and decision makers is not interested in mathematical models. Mostly, they are interested in the different consequences of the single alternative relative to others. Here, a deficit might exist concerning the translation of model output into information accessible to laymen stakeholders and decision makers.

4 CASE STUDY

Reservoirs play a dominant role in water resources for many reasons. They are the most efficient measure to influence runoff conditions by storing water for later consumption or other purposes. They add to flood protection, but they are also considerable sources of risk concerning dam failure. The multi-function of such reservoirs becomes more complex, when several reservoirs are combined in a system. The operation of such systems ususally is the result of longterm heuristic optimisation. Until recently it was argued that mathematical models for simulating reservoir systems must be tailored models due to the fact that reservoir operation rules can not be formulated in a generic mode. Lohr [8], however, showed that most likely this is possible. His work is integrated into the model TALSIM, which was developed on behalf of the State Agency for the Environment Northrhine Westfalia. The model is described in detail in Ostrowski et al [9]. Table 2 contains a brief description of the simulation modules combined in TALSIM. Figure 5 shows a screenshot of the model graphical user interface. This indicates that the user can simulate arbitrary surface water

Table 2: Pre-defined system elements in the model TALSIM

Element	Icon	Characteristics	Outputs
Sub catchment		- Soil parameters - Land use - topography	- Surface runoff - Base flow - Total flow
External Inflows		- Flow import node from beyond system boundaries	- Total flow
Transport reaches		- Flow deformation - Retention	- Deformed outflow
Consumer		- Consumer extractions - Import from other regions - Return flow to system	- Return flow - External Inflow - Total outflow
Separators		- Division rule	- Two outflows
Storages - Reservoirs		- Stage-Volume-Function - Stage-Area-Function - Hydraulics of operating gates - Operation rules	- Releases - Storage content

systems as long as its elements can be represented by the simulation modules provided. The system represented in the figure is the WVER system (Wasserverband Eifel-Rur [10]). Although small in size it is one of the most complex systems in Germany. Once the existing system is represented correctly being proven by comparison with measurements, systems changes or changes of operation rules can be simulated. As a hydrological model is incorporated in the model, also climate change impacts can be identified by simulation of potential future weather scenarios or the model can be run in realtime mode for extreme flood management. A recent example of model integration/coupling is given by Klawitter et al. [11] in this conference. Muschalla [12] coupled an integrated modelling system with an optimisation scheme also presented here.

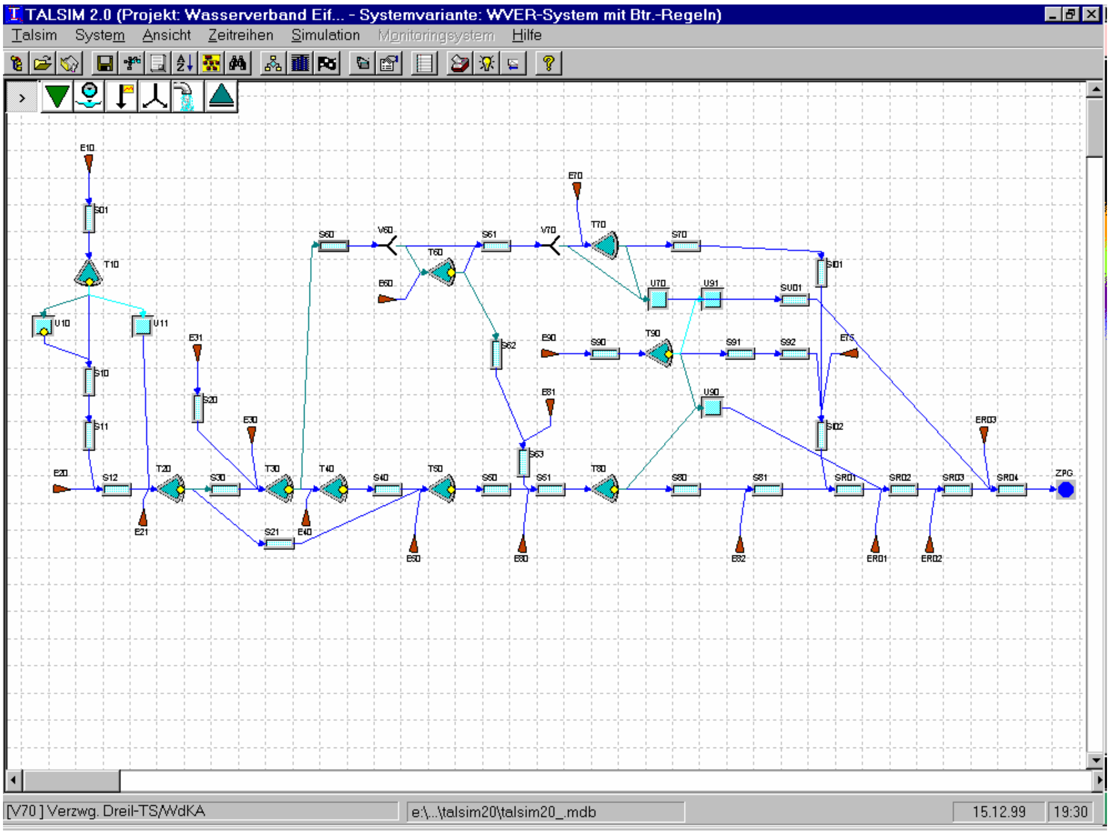


Figure 5 : Graphical user interface and the reprentation of a complex reservoir system

In general a water resources board is confronted with several types of decisions. The first catagory covers system changes, e.g. extensions such as additional reservoirs or connections. The second one aims at optimum reservoir operation rules under changing objectives and boundary conditions. Finally, under emergency conditions e.g. during extreme floods, real time decisions have to be made on the control of flood gates.

The question arises to which extent DSS can really support the decision making process. Clearly, a model and formal optimisation procedure cannot decide as it does not include the subjective judgement involved in non technical assessment. The major advantage of models is the provision of improved transparency. By setting up models and by controlling optimisation methods the knowledge of the system analysed is considerably improved. By running sensitivity analyses and by comparing sets of solutions relatively to each other the chance to come to a good decision is certainly higher than without such investigations. However, the uncertainty involved in assumptions, data, modelling approaches, objective functions and interpretation and assessment of results prevents the users of DSS to automatically come close to a good or even optimum decision. Limitations exist when modelling results have to be translated to a language which can be understood by decision makers. It is evident that the successful application of a DSS requires interdisciplinary approaches. E.g. in the case study the change of flows and water levels in the downstream river systems has to be adequately communicated to ecologists, economists and sociologists to make them assessible. Information drawn from models being trivial for the engineer might be impossible to understand by other disciplines. In this repect, communication skills might be as important as expert modelling knowledge.

5 CONCLUSIONS AND OUTLOOK

In engineering practice the intensive use of models is required and state of the art. In water resources management sectorial models have been integrated in more complex modelling packages, providing substantial support to the planner. These models are also becoming part of decision support models. Here, engineers tend to overestimate the role of models in the overall decision process when ecologic, social and political criteria have to be equally assessed. It is due time that better links between the engineering world and society are established. Only when solutions being optimal from the technical point of view are well communicated and combined with other issues they will have a better chance to survive in the decision process. Two options for improvement seem to be feasible. The first path is to integrate other then technical issues into the modelling scheme which seems at least possible for economic issues, partly this might also be possible for ecologic issues. The other path is the development of better communication and discussion procedures accompanied by special mediation.

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